7. Quantum Electronics

A. LASER APPLICATIONS

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7.1 Ultrahigh-Resolution Spectroscopy and Frequency Standards in the Microwave and MM Wave Regions Using Optical Lasers

Air Force Rome Air Development Center (in collaboration with C.C. Leiby Jr)
U.S. Air Force - Rome Air Development Center (Contract F19628-80-C-0077)
Philip R. Hemmer, John E. Thomas, Shaoul Ezekiel

In this program we are considering an attractive possibility for obtaining ultrahigh resolution in the microwave and mm regions using optically induced Raman transitions in atomic beams. The research is centered around the interaction of two laser fields with a three level system in an atomic beam. Of particular interest is the basic study of coherent two-photon excitations in a folded three level system in which exceedingly narrow resonances can be obtained when the intitial and final levels are long lived states. As is well known, the linewidth is determined only by the intitial and final level decay rates for a Doppler free system such as an atomic beam.

In order to achieve such narrow linewidths, laser frequency jitter must be eliminated and the time the atom spends in the excitation field must be made as long as possible to reduce the transit time linewidth. We eliminate laser jitter by correlating the jitter in the two lasers since the transition frequency of interest depends on the difference in the laser frequencies. In summary, we are able to make a transition from the first level to the final level indirectly via the intermediate level and achieve a linewidth equivalent to that obtained by a direct transition from the first to the final level using a microwave or mm wave source.

Our initial experiments have been conducted with an atomic beam of sodium and dye lasers. In this case the difference frequency is 1772 MHz. Laser jitter in each beam was correlated by simply deriving one laser frequency from the other by an acousto-optic frequency shifter driven at 1772 MHz. A linewidth of 650 Hz was achieved by using Ramsey's separated oscillator method to reduce the transit time linewidth. We have also stabilized the 1772 MHz oscillator that drives the acousto-optic shifter to this narrow linewidth and achieved a short term stability equivalent to that in a C_2 atomic beam if subjected to the same conditions of our setup.

We plan to increase the separation between Ramsey regions further so as to achieve a linewidth on the order of 100 Hz to study various sources of level shifts. We also intend to extend this technique to the mm waveregion of the spectrum.

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7.2 Resonant Light Diffraction by an Atomic Beam

National Science Foundation (Grant PHY79-09739)
Joint Services Electronics Program (Contract DAAG29-80-C-0104)
Bruce W. Peuse, Mara G. Prentiss, Shaoul Ezekiel

We have observed resonant light diffraction by an atomic beam of 2-level sodium atoms. This grew out of an effort to develop new techniques of performing absorption spectroscopy in low density atomic beams, that are capable of achieving quantum noise limited sensitivity. As a result of using such techniques, we found that the absorption lineshape exhibited an asymmetry even for weak fields and the magnitude of this asymmetry depended on the position and size of the detector. In contrast, the lineshape determined by collecting the fluorescence from the same atoms did not exhibit any asymmetry. Moreover, we measured the on-resonance and also the off-resonance absorption as a function of detector position.

We explain the observed distortion in the absorption lineshape and the spatial absorption behavior as a manifestation of the interference between light scattered by the atoms with the excitation beam at a given position of the detection plane. In other words, we have observed a diffraction-like pattern due to the laser beam propagating across a thin atomic beam. The difference between on-resonance and off-resonance behavior is explained by the dependence of the phase of the scattered field on frequency. Detailed calculations are in progress and preliminary results show close agreement with observed data.

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7.3 Precision Atomic Beam Studies of Atom-Field Interactions

National Science Foundation (Grant PHY79-09739)
Joint Services Electronics Program (Contract DAAG29-80-C-0104)
Bruce W. Peuse, Philip R. Hemmer, Shaoul Ezekiel

We have performed a high resolution study of the interaction of two monochromatic laser fields with a prepared three-level cascade system in an atomic beam of sodium. One laser, at 5890 A, was held fixed near resonance with the first and second levels while the second laser, at 5688 A, probed the transition between the second and third levels. The intensity of the probe field was kept low while the intensity and also the frequency of the first, or pump, laser were varied.

Such experimental studies provide important and fundamental information about the nature of atom-field interaction and can be compared directly with theoretical predictions.

In the case of a weak pump, our data showed a probe linewidth of approximately 3.1 MHz, determined only by the relaxation rates of the first and final levels with no contribution from the second level. This lineshape was compared with theory and the agreement was excellent.

The probe lineshape in the presence of a strong pump exhibited a splitting due to the ac Stark effect but the splitting showed strong asymmetry. The peculiarities of the observed strong field lineshape was explained by including in our calculations the recoil the sodium atoms experience as they traverse the strong pump field. In this way, we were able to explain both the asymmetry as well as the additional broadening that was observed.

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7.4 Passive Ring Resonator Method for Sensitive Inertial Rotation Measurements in Geophysics and Relativity

Air Force Geophysics Laboratory (Contract F 19628-79-C-0082)
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Precision measurement of inertial rotation is of much interest in a number of areas, such as navigation, geophysics, and relativity. The geophysical applications include the measurement of the various effects that cause fluctuations in the earth's rotation rate Ω_E, ranging from 10^{-7} to $10^{-9}\Omega_E$, for example, nutation, precession, wobble, and tidal-friction effects. The relativistic effects range in sensitivity from 10^{-9} to $10^{-11}\Omega_E$ and include measurements of the preferred frame and the drag parameters.

The advent of the laser in 1960 rekindled the interest in the use of the Sagnac effect for sensing inertial rotation by optical means. Several approaches to implementing the Sagnac effect have been under investigation. These include active techniques, such as the ring laser gyro, and passive techniques employing passive ring resonators or multiturn fiber-optic interferometers. In all these approaches, the measurement sensitivity scales with the area enclosed by the light path. Typically, to reach the sensitivity needed to measure the geophysical and relativistic effects mentioned previously, it is necessary to consider areas between 10^2 and 10^4 m^2.

Our research effort centers around the passive resonator technique. Our present setup is a square cavity, 70 cm on a side, mounted on a super invar table. The difference between the resonance frequencies of the cavity for clockwise (cw) and counterclockwise (ccw) propagation induced by inertial rotation is measured by a 1/2-mW He-Ne laser, mounted external to the cavity. We have reduced the short-term random drift to about $3 \times 10^{-4}\Omega_E$ (where Ω_E is earth rotation rate) in an averaging time of 30 seconds which is close to the photon shot noise limit in our set-up. The study of long term drift is in progress.

We are also using our present ring resonator configuration to perform precision studies of Fresnel drag. By employing a sinusoidally oscillating optical flat within the resonator, we hope to test the relativistic addition of velocities in a medium (Fresnel drag) to one part in 10^4. In addition we should be able to test the dependence on the refractive index of the material used as well as its dispersion.

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7.5 Closed Loop, Low Noise Fiberoptic Rotation Sensor

Joint Services Electronics Program (Contract DAAG29-80-C-0104)

Mara G. Prentiss, James L. Davis, Shaoul Ezekiel

The fiber-optic gyroscope has been receiving considerable attention for the past several years. A number of different approaches have been studied, and as these studies progress a number of problems were uncovered.

Our present approach employs a 200 m long fiber wound around a 19 cm diameter spool and operated in a closed loop mode. Our measurement approach is based on the use of two acousto-optic frequency shifters placed within the fiber interferometer for providing nonreciprocal phase modulation as well as nonreciprocal frequency offsets needed in closed loop operation. Short-term random drift is about 0.03^{o}/hr for averaging times of 30 seconds which is close to that predicted by the photon shot noise limit in our set-up. The long term performance departs from the photon noise limit and considerable effort is at present directed into the sources of long term drift.

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7.6 Intensity-Induced Nonreciprocity in a Fiberoptic Gyroscope

Joint Services Electronics Program (Contract DAAG29-80-C-0104)
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We have predicted and observed an intensity-induced nonreciprocity in a fiberoptic Sagnac interferometer which is being developed for absolute rotation sensing. We found that a nonreciprocal phase shift of 1.4×10^{-6} radians can be generated by a one microwatt power difference between the oppositely propagating light beams. Our fiber is 200 m long with a core diameter of 4.5 microns, and wound on a 19 cm diameter spool. The intensity dependent nonreciprocal phase shift, which is attributed to a four wave mixing process in the quartz medium, is equivalent to a rotation rate of 0.2^{o}/hr in the present geometry, and therefore stresses the need for a strict intensity control in precision fiber rotation sensors.

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7.7 Measurement of Natural Predissociation Effects in Iodine Molecules

Joint Services Electronics Program (Contract DAAG29-80-C-0104)
National Science Foundation (Grant PHY 79-09739)
Robert E. Tench, Donald R. Ponikvar, Shaoul Ezekiel

In our continuing study of the interaction of two monochromatic fields with folded 3-level systems in vapors, we have performed extremely high resolution measurements of Doppler free resonances in I_2. With weak copropagating pump and probe fields we have observed linewidths as narrow as 50 kHz, vapors, we have performed extremely high resolution measurements of Doppler free resonances in I_2. With weak copropagating pump and probe fields we have observed linewidths as narrow as 50 kHz, determined, in principle, by the relaxation rates of the first and final levels with a small contribution from the relaxation rate of the intermediate level. For counterpropagating fields we have observed a probe linewidth of about 150 kHz that is determined primarily by twice the relaxation rate of the intermediate level. We are using this doubling of the intermediate level relaxation rate to perform precision measurements of the natural linewidths of the many hyperfine transitions in the P(13) 43-0 and R(15) 43-0, B-X transitions at 5145 Å. Because of natural predissociation effects in the I_2 molecule, the natural width of each hyperfine component will be different. Our precision measurements will therefore enable us to study in more detail such predissociation phenomena.

Since molecular iodine is being considered as a reference molecule in the visible region of the spectrum, precision linewidth and lineshape measurements of individual hyperfine components as well as the spacing between components is of much interest.

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B. NONLINEAR PHENOMENA

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7.8 Picosecond Optical Signal-Sampling Device

National Science Foundation (Grant DAR80-08752)

Hermann A. Haus

Optical waveguides have broad absolute bandwidths and have small dimensions. These two properties make them ideal for high-speed switching and signal-processing applications. Two kinds of microwave-modulation structure can be employed-traveling-wave and standing-wave structures. Examples of the former have been described in the literature over the past few years.[1-3] We are concentrating on standing-wave structures. The modulation frequencies achievable in the latter are higher than in the former, whereas the former can perform a greater variety of modulation functions.

The standing-wave structure currently under development is a shorted-strip-line phase modulator on one arm of a Mach-Zehnder interferometer,[4] a schematic of which is shown in Fig.7-1.

The structure has been designed to resonate at 10 GHz, and has relatively low Q so that the modulation frequency can be changed over a bandwidth of, at least, 10%. A cw laser input is converted into a stream of pulses separated by 50 psec with 16 psec full width at half-maximum. We have not yet been able to make a direct measurement of the pulse shape, because optical detectors are not fast enough to detect these pulses. The conventional means of detection by second-harmonic generation which measures the correlation function of the optical intensity cannot be employed directly because the optical intensity is too low. Spectral measurements of the optical output have been performed by a scanning Fabry-Perot interferometer and they have confirmed that modulation is occurring at 10 GHz, producing the theoretically predicted spectrum. From the spectrum one can infer the shape of the pulse train, assuming that the unobservable phases of the side bands are those predicted theoretically.

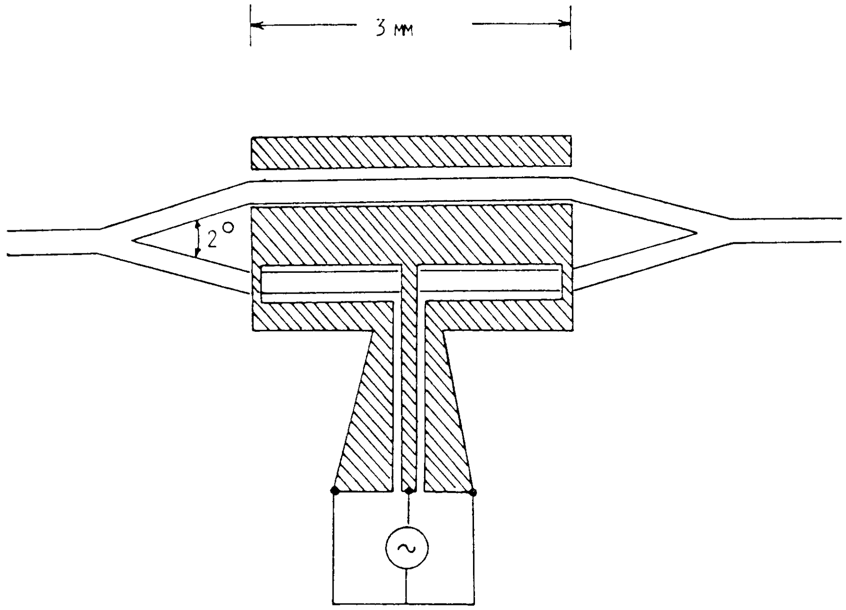

Figure 7-1: Interferometric sampler with strip-line resonator

The strip-line structure cannot be extended unmodified to higher modulation frequencies, partly because the losses become excessive, partly because the transit time of the optical radiation through the structure becomes larger than the modulation period. Both of these effects can be overcome through the use of periodic electrode structures fed transversely (as opposed to the strip line that is center-excited and propagates along the thin lossy electrodes forming the modulation structure). Once we have fully demonstrated successful modulation at 10 GHz, we shall turn to the fabrication and experimental testing of structures designed for higher modulation frequencies.

The device described thus far is an optical sampling device. Without any change in the modulating microwave structure, one may convert it into a demultiplexer (Fig.7-2). The waveguide interferometer output is not combined in a waveguide Y, but fed into a waveguide coupler. If the spacing between the waveguides is properly chosen, for a given voltage applied to the electrodes, output can be produced in either one or the other of the output waveguides. An incoming pulse train can be demultiplexed into the two waveguides by a sinusoidal microwave drive synchronized with the pulse-repetition frequency. The same device, run backwards with input and output interchanged, operates as a multiplexer. We plan to fabricate such a device after completion of the work on the sampler.

In summary, the main goal of our work is to demonstrate the feasibility of sampling, multiplexing, and demultiplexing of optical radiation in optical waveguide structures. An obvious use of these new devices is in a sampling instrument in which incoming radiation is sampled and demultiplexed into parallel channels. Each of the demultiplexed trains of sample pulses would be slowed down to a rate consistent with the speed of available optical detectors.

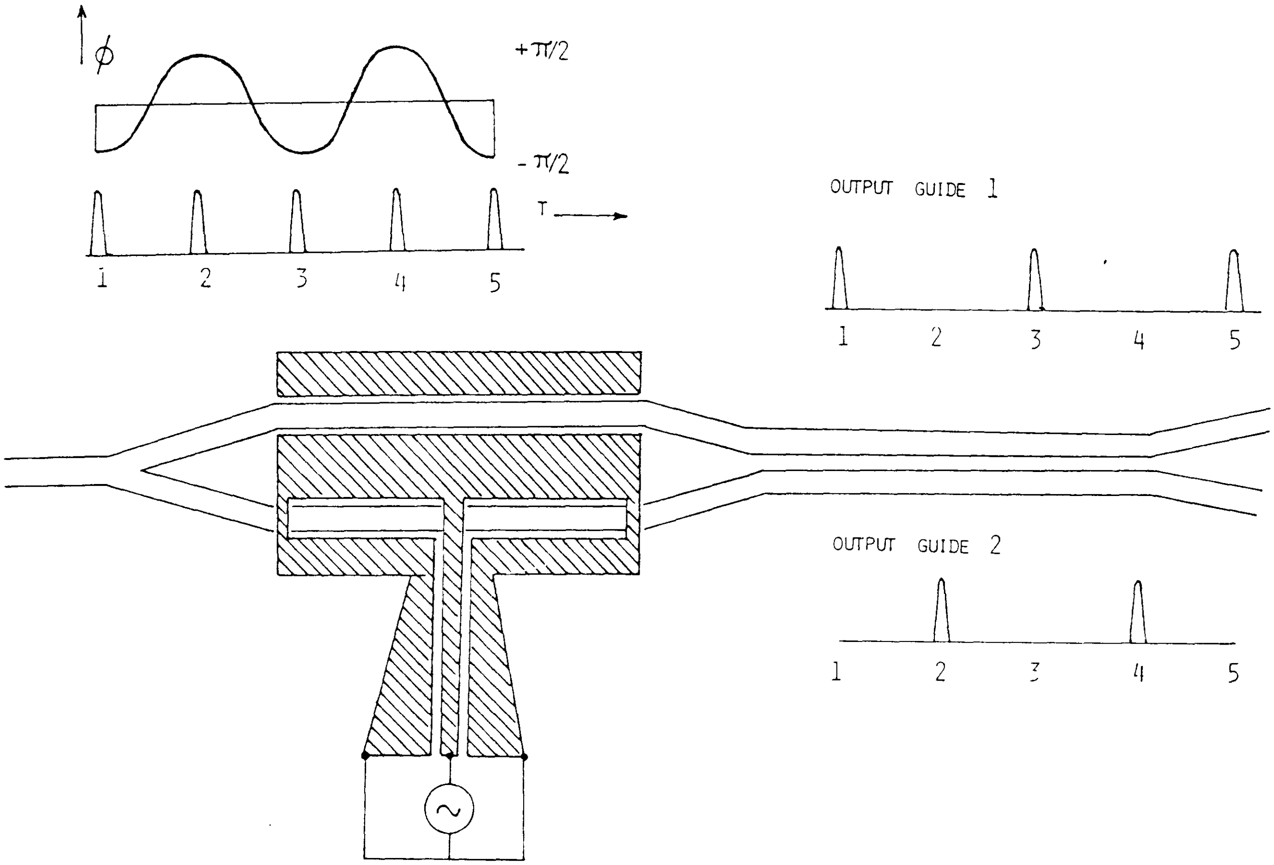

Figure 7-2: Demultiplexer

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7.9 Devices for High-Rate Optical Communications

National Science Foundation (Grant ECS79-19475)

Clifton G. Fonstad, Herman A. Haus

a. Monolithic Mode-Locked Lasers

Force mode-locked diode lasers, which operate in an external cavity, can produce optical pulses of under 5 picoseconds duration at repetition rates exceeding 5 Gbs. Such pulse trains, used with high-frequency guided-wave optics components, could form the basis of 100 Gb/S fiber communications systems. Existing lasers, however, are mode-locked in an external cavity, and the associated mirrors, lenses, optical positioners, and optical bench are far too cumbersome to be useful in anything but a research laboratory environment. Consequently, we are studying very long, nonuniformly excited diode lasers which can be mode-locked without the use of an external cavity.

In an initial portion of this program, we have done research on multisegment stripe-contact laser diodes of more conventional length.[1] These devices, which have eight separate contacts along the stripe, are interesting devices in their own right, and themselves promise to be useful in optical communications because of the enhanced nonlinearities in their current-light output characteristics arising from the nonuniform excitation. Small-signal gain (external-differential quantum efficiencies in excess of 100% per mirror), switching, and hysteresis are all observed for various current combinations. A computer model capable of describing this behavior using simple device models has also been developed.

In our recent work, very long multisegment lasers have been fabricated with the aid of Dr. A. SpringThorpe of Bell Northern Laboratories (the original lasers were also fabricated in material supplied by Dr. SpringThorpe). These devices have 8 segments, each 875 μm long, i.e., a total length of 7 mm. The round-trip time of optical pulses in such long lasers should correspond to a frequency of approximately 6 GHz. Testing of these devices is just beginning.

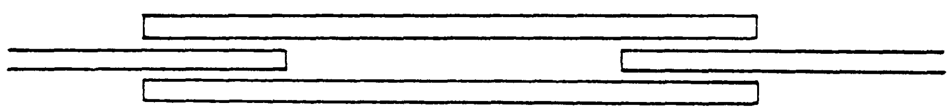
b. Guided-Wave Optics in InP

We have completed an extensive set of measurements of the losses and coupling lengths for TM modes and TE modes in unbiased, metal-gap optical waveguides on n/n^+ InP epilayers (the epilayers used in this study were supplied by S. Groves of MIT Lincoln Laboratory).[2] A variety of gap widths (4 μm to 12 μm) and coupled-guide spacings (2 μm to 6 μm) were investigated. Losses for the TM modes were quite high (>6 cm^{-1}) but these modes were well guided. TE modes, on the other hand, are much less lossy (~2 cm^{-1}) but are very poorly confined in the absence of an applied field (the present metal electrodes do not form good Schottky barriers). Coupling lengths (3 db) for the TM modes were as short as 2 mm in the 6 μm guides, separated by 4 μm. The guiding-index step seen by the TM modes is presently being determined.

Work is continuing both on improving our own growth capabilities so that we can produce guide-quality epilayers and on techniques which may permit us to make guides directly in the substrates. Structures are being considered which will allow us to apply bias fields to the lateral guiding regions, and thus to produce switches and modulators. The ultimate goal remains to produce very high-speed coupler switches which can be driven at up to 100 GHz for multiplexing and demultiplexing trains of picosecond-wide optical pulses.

c. Three-Waveguide Couplers

A final significant result of this effort has been our proposal of a new three-waveguide directional coupler and switch.[3] Waveguide bends and Y's are not easily fabricated in III-V semiconductor waveguides because the index guiding achieved in these materials is not as "tight" as is achievable in the more popular, but ultimately less adaptable $LiNbO_3$. We have proposed a means of producing waveguide couplers and Y's without bends with three-waveguide[3] and five-waveguide couplers (see Fig.7-3).



INTERFEROMETER WITH 3 - WAVEGUIDE " Y "

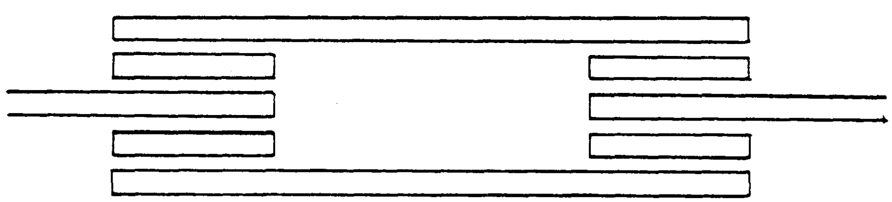


Figure 7-3: Interferometer with 5-Waveguide "Y"

In this structure two guides are coupled, not by bending them to bring them into close proximity, but by simply inserting a third guide between them. The coupling length of this three-guide structure is only 1.4 times that of a similarly spaced pair of guides, and the need for bends is completely eliminated. This is a very important result because in weakly confining III-V guide structures any curves must have large radii to avoid introducing large losses. The use of three-guide couplers should therefore greatly reduce the size of future guided-wave optical circuits. We are presently studying such couplers experimentally.

This idea can also be applied to Y's. If a waveguide is in proximity to two symmetrically placed outer waveguides, then radiation in the center waveguide is transferred fully and symmetrically to the outer guides, for an appropriate length of the center guide. Dr. F.J. Leonberger and J. Donnelly of Lincoln Laboratory have recently used this idea and have fabricated waveguide Y's in this manner in GaAs ridge waveguides.

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7.10 Picosecond Optics

Joint Services Electronics Program (Contract DAAG29-80-C-0104)

Hermann A. Haus

Our laboratory was the first to mode-lock a semiconductor laser diode in an external resonator.[1] Since then the work has been extensively duplicated and extended in other laboratories.[2] The purpose behind the mode-locking effort is to fabricate a source of short pulses compatible with waveguide optics. One further step in this direction was accomplished when we succeeded in modelocking an InGaAsP diode in an external resonator consisting of a selfoc lens. The dimensions of the system are greatly reduced in this arrangement, and one may "butt" the highly compact source onto an optical waveguide system. The ability to shorten the external resonator enabled us to produce the highest modulation frequency yet achieved for 100% modulation of a laser diode, 9.4 GHz.[3]

All of this work is aimed at the development of high-speed optical modulation and signal-processing elements. These, in turn, are needed if waveguide optics is to gain acceptance in electronic systems. Waveguide optics, or the more ambitiously named Integrated Optics, will not compete seriously with integrated electronics in all those functions that can be performed electronically . This is due to the higher power requirements and more complicated topology of optical, as opposed to electrical, "circuits." Waveguide optics can perform certain signal-processing functions at greater speeds than electronic circuits can, and for this reason one may anticipate that opticalsignal processing will gain acceptance in some special applications.

The modulator structures described in Section 7.2 are linear timedependent structures. For high-speed optical signal processing one needs nonlinear optical devices. The current interest in devices exhibiting optical bistability is motivated by the need for direct optical signal processing.

Optical nonlinearities are weak, and hence optical signal processing requires very high optical intensities (100 Mw/cm^2) and long interaction lengths. The long interaction lengths cause no more than processing delays if the interacting optical signals are traveling waves (rather than standing waves, as in a resonator) and the signals are processed in the "pipelining mode."

We are developing an optical exclusive OR gate (XOR) capable of processing picosecond optical pulses of peak powers on the order of 100 watts. The XOR gate is chosen because singly, or in combination with only a few gates, it can perform important signal-processing functions of coding or decoding.

A schematic of the structure is shown in Fig. 7-4. A cw pulse stream is produced by a sampler from a cw source in the manner described in Section 7-2 and fed, in one polarization (TE), into the central guide of the waveguide interferometer as the "probe" signal. Control signals consisting of pulses synchronized with the probe pulses are fed in the perpendicular polarization (TM) into the other two guides.

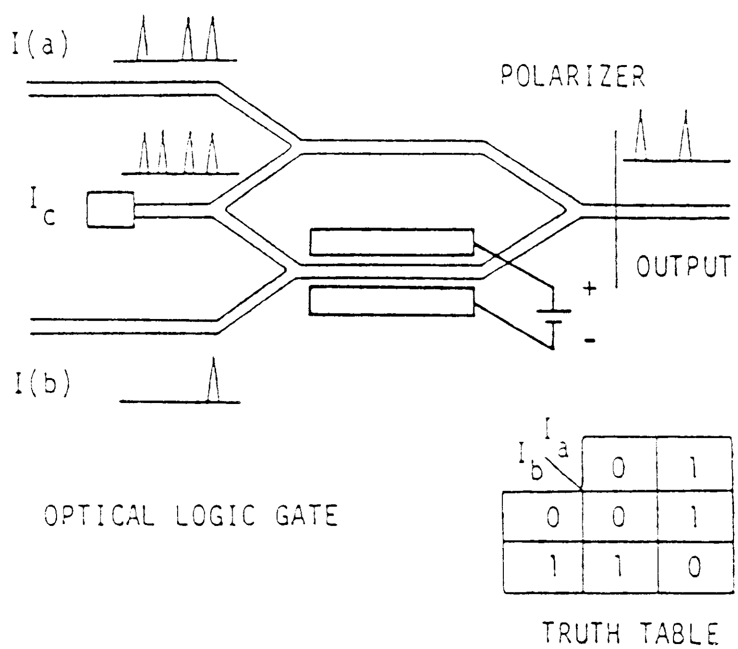

Figure 7-4: Schematic vies of the integrated XOR gate

A phase shift of π is produced by an applied voltage on the electrodes in one of the interferometer arms. In the absence of control pulses, the output of the interferometer is zero; with a control pulse of appropriate power in either one of the control guides, a phase shift of π is produced due to the nonlinear index change, and an output probe pulse of proper polarization is produced. With control pulses in both guides no output occurs.

This is the operation of an XOR gate. The control pulses need not be phase-coherent; the only requirement is that phase coherence be maintained in the two arms of the interferometer.

We are currently testing an interferometer built in $LiNbO_3$ to operate at $\lambda = 7500$ Å. The powers required are sufficiently large that optical damage (photorefraction) peculiar to $LiNbO_3$ is to be expected over extended periods of operation. Yet we have chosen visible radiation and $LiNbO_3$, both for ease of alignment and experience in fabricating the guides. We hope that we can avoid the damage by maintenance of symmetric excitation over limited running times.

We have made further studies of polarization transformation due to optical damage in waveguides in X-cut, Y-propagating $LiNbO_3$, and discovered previously unreported effects. It was observed that, for cw intensities on the order of $50 \cdot 10^3$ w/cm^2, full transfer of TM excitation into TE takes place in a single-mode waveguide in $LiNbO_3$ after 10-20 sec running time. The reverse does not occur - TE is not transformed into TM.

We were able to explain the effect by a process fittingly denoted as Doubly Degenerate Four-Wave Mixing. The photorefraction provides a "gratinglike" coupling with a periodicity that automatically compensates for the large-phase mismatch between TE and TM waves in the crystal orientation used. The grating is produced by the interaction of the TE and TM waves - the stronger the TE wave the stronger the grating - this is an effect that exponentiates. We believe that further study of this unusual effect will yield more information on photorefraction in $LiNbO_3$.

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C. GRATING STRUCTURES

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7.11 Surface Acoustic Wave Gratings

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Several types of surface acoustic-wave (SAW) devices operate on the principle of coherent reflection of the waves from gratings. The gratings used are generally shallow with a depth equal to a few percent, at most, of the grating period. Thus, apart from a small reflection from each groove edge, the SAW, to first order, propagates in the grating undisturbed. Small deviations from this lowest order model, which result in a slowing and attenuation of the wave in a grating, are important in some critical devices. Resonators, in which a surface acoustic wave bounces between two gratings as in a Fabry-Perot cavity, are used as high-Q frequency standards. Here, frequency shifts occur due to the propagation in a finite-depth grating. Reflective-array compressors are used to compress chirped radar waveforms which are often up to 80 μsec in length. The frequency within the waveform varies monotonically over the length of the pulse. The compressor, in effect, adds the signal at the head of the pulse to the signal at the tail with the correct phase and amplitude. Thus transit time and attenuation within a grating must be accurately controlled.

Our work on surface acoustic-wave grating structures has a dual goal: (a) development of methods of analysis of grating structures that are simpler than those generally employed, and (b) utilization of simple analytical methods in the design of novel structures using the properties of SAW gratings.

The work on methods of analysis had as its original purpose the prediction of frequency shifts of SAW resonators as a function of (ion-milled) groove depth and shape. We developed a variational principle that predicts the frequency to a greater degree of accuracy than the acoustic-field trial solution used for the prediction.[1,2] An error that occurred in the literature was uncovered.[3a,b]

In an attempt to increase the range of validity of the variational principle, we extended it to the analysis of gratings that radiate into the bulk crystal. This is a little-explored application of variational principles to systems which are not "self-adjoint." We have developed the variational principles for this purpose and tested it on examples in optics that have been previously treated by a perturbation approach, showing excellent agreement with, and in some instances improvements over, previous results. The examples treated are radiation from a corrugated optical waveguide and radiation from bent optical guides. The results are presented elsewhere.[4]

To test the theory experimentally, we have used SAW structures previously fabricated for the purpose of measuring the phase shift produced by gratings. In these structures the loss in an acoustic beam propagating in a grating was compared with a parallel beam not propagating in the grating, and the grating loss due to radiation into the bulk was measured as a function of frequency in a number of configurations. The experimental results agree very well with theory.[5]

The work directed toward the development of new grating structures is done in collaboration with C. Hartmann of RF Monolithics. He is interested in the realization of unidirectional transducers to reduce both insertion loss and triple-transit effects. He proposed to accomplish this with a combination of interdigital transducers and interspersed grating structures. Our previous theoretical work on grating structures is particularly suited to the analysis of such structures. More interestingly, we are developing synthesis algorithms for the realization of desired scattering parameters over specified bandwidths. We have improved upon approximate procedures developed by Kogelnik, Cross, and Alferness[6-8] for optical filter design for this purpose and found encouraging results. Transducers "designed" according to these methods "performed" close to the starting specifications when subjected to a full numerical analysis. We have not done any experiments as yet on transducers of these novel designs. Dr. Hartmann will assist us in validating the designs by providing us with transducers fabricated according to our design specifications.

An important problem for interdigital transducers is the spurious responses due to higher-order transverse modes. We have done analyses of transverse modes in the past,[9,10] and intend to reinvestigate the problem in an effort to control the spurious responses.

References

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